MEMORANDUM FOR: SAF/PAS
1690 Air Force Pentagon - 5D227
Washington DC 20330-1690

MAY 31 2002

FROM: Francis G. Hinnant, Col, USAF
Associate Director of Acquisition
NPOESS Integrated Program Office
8455 Colesville Rd, Suite 1450
Silver Spring, MD 20910

SUBJECT: Paper approval for: Measurement of Noise in Large Area $Hg_{1-x}Cd_xTe$ Photovoltaic Detectors: Validation/Analysis of Results

Enclosed are the required ten (10) copies of the subject paper. This paper will be released at the annual meeting of SPIE (International Society for Optical Engineering) in July of '02. It was written by, and will be presented by employees of ITT Industries.

The program office has reviewed the information in the attached papers and found it appropriate for public disclosure without change.

Point of contact on this matter is Capt. Christina Muth, NPOESS IPO/ADA at 301-427-2084 (Ext. 114).

Attachment: Presentation—10 copies

# Measurement of Noise in Large Area $Hg_{1-x}Cd_xTe$ Photovoltaic Detectors: Validation/Analysis of Results

D.S. Smith
ITT Industries, 1919 W. Cook Road, Ft. Wayne, IN 46814

A.I. D'Souza
DRS Sensors & Targeting Systems, 3400 Miraloma Avenue, Anaheim, CA 92806

## ABSTRACT

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Cross-track Infrared Sounder (CrIS) is a Fourier Transform interferometer-based sensor used to measure earth radiance at high spectral resolution and low spatial resolution. Measured radiance data are analyzed by end users to provide pressure, temperature and moisture profiles of the atmosphere. The CrIS instrument contains Mercury-Cadmium-Telluride (MCT) photovoltaic (PV) detectors with spectral response in the SWIR ($\lambda_c \sim 5$ µm at 98K), MWIR ($\lambda_c \sim 9$ µm at 98K) and LWIR ($\lambda_c \sim 15$ µm at 81K) ranges. The CrIS instrument requires large area detectors (1mm diameter) with state-of-the-art detector performance at temperatures attainable with passive cooling.

In the case of the LWIR bands noise associated with the detectors limit the instrument performance. In this paper we describe a study of the noise characteristics of a sample of CrIS MCT PV detectors, emphasizing acquisition and validation of *1/f* noise measurements for these devices. Interesting aspects of the *1/f* noise dependence on bias-voltage and bias-current are noted. The results are analyzed further in a companion paper[1] that emphasizes the relationship between leakage current mechanisms in the diodes and *1/f* noise observed.

**Keywords:** detectors, noise, noise measurement

## 1. INTRODUCTION

Accurate measurement of *1/f* noise (or noise in general for that matter) requires that we determine that the equipment used to measure the noise does not limit the measurement of the components under scrutiny. In all measurements described herein we used a commercially available TIA (**Trans**I**mpedance** **A**mplifier) from

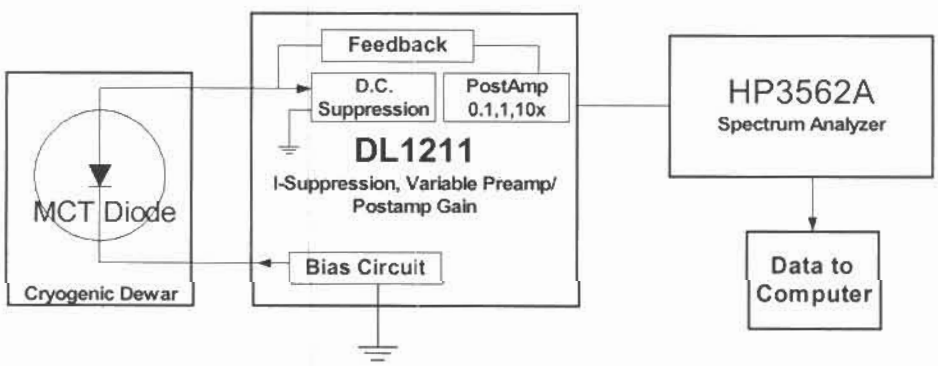


**Figure 1 HgCdTe longwave Diodes were tested under no background flux in a blinded dewar. The DL1211 is a current preamplifier capable of diverting d.c. current resulting from the bias on the detector from the feedback circuit reducing the d.c. offset at the output of the DL1211's preamp.**

DL Instruments (model DL1211) to transform noise current density of the detectors under test to a noise voltage density measurable by a HP3562 spectrum analyzer, as shown in figure 1.

The DL1211 (connected to the detector through a dewar bulkhead) is an instrument used in many laboratories to perform detector signal and noise measurements. According to the manufacturer of the DL1211 its feedback resistors, which range from 1 kΩ up to $1 \times 10^{11}$ Ω, suffer from low *1/f* noise. The level of the *1/f* noise associated with the DL1211 is indicated by the measurement results offered herein.

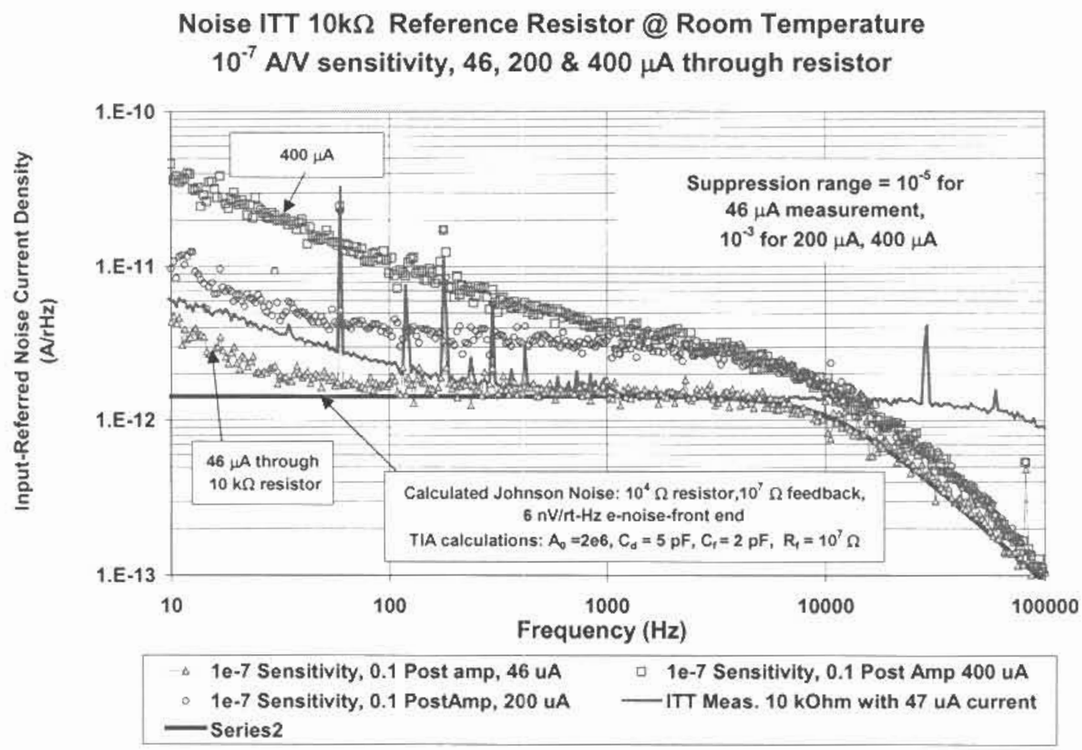


**Figure 2 Noise-current spectral density for a 10 kΩ resistor for several currents in the resistor. The suppression range affects the white noise of the measurement as well as the 1/f components.**

## 2. Resistor Measurements

To simulate the conditions for operation of the DL1211 during HgCdTe diode testing we decided to study a "known" component with bias currents similar to the HgCdTe leakage currents. We measured spectral noise voltage density produced by a 10 kΩ resistor with various bias currents passing through the resistor. We chose this value because the photodiodes under test exhibit dynamic impedances on the order of 10 kΩ. Shown in figure 2 are noise current spectral density (NSD) plots of the 10 kΩ resistor referred to the input by scaling the voltage noise spectral density using the DL1211 preamp transimpedance and post-amp gain. (The noise voltage spectral density is divided by the feedback resistor value and the DL1211 post-amp gain.) The lowest noise curve shown (indicated with triangles) was acquired with 46 μA bias current in the resistor. We also show a plot of calculated NSD (solid curve constant in value between 10 and 100 Hz) for 10 kΩ and a 6 nV/rHz voltage noise at the front end of the DL1211. Further, the resistor NSD was measured at ITT using a custom-built preamp used for detector testing. The data for the ITT characterization are shown in the solid noise curve and compare well with the DL1211 results. Since the DL1211 results were actually slightly better than the results for the ITT custom preamp it was concluded that no further comparison of the performance of the DL1211 relative to the ITT custom preamp was needed. Data reported herein (except for the ITT-measured NSD in Figure 2) were acquired with the DL1211.

Expected noise, $I_n$, in figure 2 is calculated using the following equations:

$$g(\omega) = \left\{ \frac{1}{A_0}\left(1 + \frac{i\omega}{\omega_t}\right)\left(1 + \frac{R_f}{R_d} + i\omega R_f (C_f + C_d)\right) + \left(1 + i\omega R_f C_f\right) \right\}^{-1} \quad \textbf{Equation 1}$$

$$i_n^2 = 4k_b\left(\frac{T_f}{R_f}+\frac{T_d}{R_d}\right)+\omega^2 e_n^2 C_d + e_n^2\left(\frac{1}{R_f}+\frac{1}{R_d}\right)^2 \qquad \textbf{Equation 2}$$

$$I_n(\omega) = i_n(\omega)g(\omega) \qquad \textbf{Equation 3}$$

where $R_f$ and $R_d$ represent resistance values of the feedback and the resistor/detector respectively. $C_f$ and $C_d$ are capacitance values associated with the feedback and input node of the DL1211. $e_n$ is front-end voltage noise of the amplifier, $k_b$ is Boltzman's constant, $T_d$ is the operating temperature of the device, and $T_f$ is the operating temperature of the DL1211 amplifier. $\omega$ is the frequency in radians/sec ( $= 2\pi f$, $f$ in Hz). Note: in many of the charts we refer to a sensitivity setting of the DL1211. The feedback resistor referred to in equations 1 and 2 is given by 1/(Sensitivity setting in $\Omega^{-1}$), i.e. DL1211 Sensitivity Setting = 1/ $R_f$.

The plot as presented in figure 2 shows noise current density with an apparent roll-off near 10 kHz. The roll-off is a result of frequency response of the DL1211 for the feedback (see equation 1) and post-amp settings used for the test, and is not a characteristic of the input noise itself (See equation 2.). Also note that shot noise is not shown because resistors do not suffer from this form of noise.

The data and calculation in Figure 2 show that with reasonable assumptions for the DL1211 preamplifier we can account for the impact of noise in the measurement circuit. This is important in establishing limits on how well we can measure *1/f* noise of the MCT diodes with the DL1211. Also note two other measured noise curves in Figure 2. In squares and circles (the two highest-level noise curves at 10 Hz) we show the noise curves of the 10 kΩ resistor measured at 200 μA and 400 μA bias currents. We acquired this data with a less sensitive bias current suppression range than used for the 46 μA measurement. Even though the *1/f* noise component increases the shapes and slopes are similar, with the *1/f* noise contribution increasing with the current. However, the unexplained behavior is the rapid increase of the *1/f* noise component with current. It appears that the *1/f* noise voltage density increased by a factor of 4 with only an increase of a factor of 2 in current flowing through the resistor. As explained in reference 1, *1/f* noise voltage spectral density in a photodiode typically scales with the current. The behavior seen in Figure 2 for the resistor suggests that there is a far more rapid increase with current for some components of *1/f* noise, or possibly that there are more sources of *1/f* noise than accounted for in our measurement. Either way we did not acquire enough data for this experiment to answer this particular question.

The white noise (flat) regions of the 200 and 400 μA spectra show a noise increase relative to the 46 μA white noise probably best associated the suppression circuitry. Since the white noise component increases far less rapidly than the *1/f* noise, one could speculate that the suppression circuit's noise is from a source (Johnson or Shot) in the suppression circuitry itself.

Further consideration of the variation of the resistor *1/f* noise with current is warranted since that is what we are attempting to measure in the MCT diodes. In figure 3 we see a comparison of the noise measured for the 10 kΩ resistor with 10 μA and 46 μA flowing through the resistor. The DL1211 settings are the same for both measurements as noted on the figure. Since both curves overlap within the apparent noise of the measurement it appears that small currents through the resistor are a weak factor for determining resistor *1/f* for this range of currents. This suggests that the DL1211 may be the source of the *1/f* noise instead of the resistor. The DL1211 is also possibly the source of the excess *1/f* noise seen in Figure 2 for the 200 μA to 400 μA cases where the noise increase depends strongly on the current.

## 3. HgCdTe Photodiode Measurements

The objective of these measurements is to determine the *1/f* noise characteristics of HgCdTe diodes for the CrIS program. We must then establish the NSD levels of the HgCdTe diodes relative to the DL1211 circuit used to characterize them to establish confidence in the measurements. In figure 4 we show a noise curves for all the HgCdTe diodes characterized in this experiment.

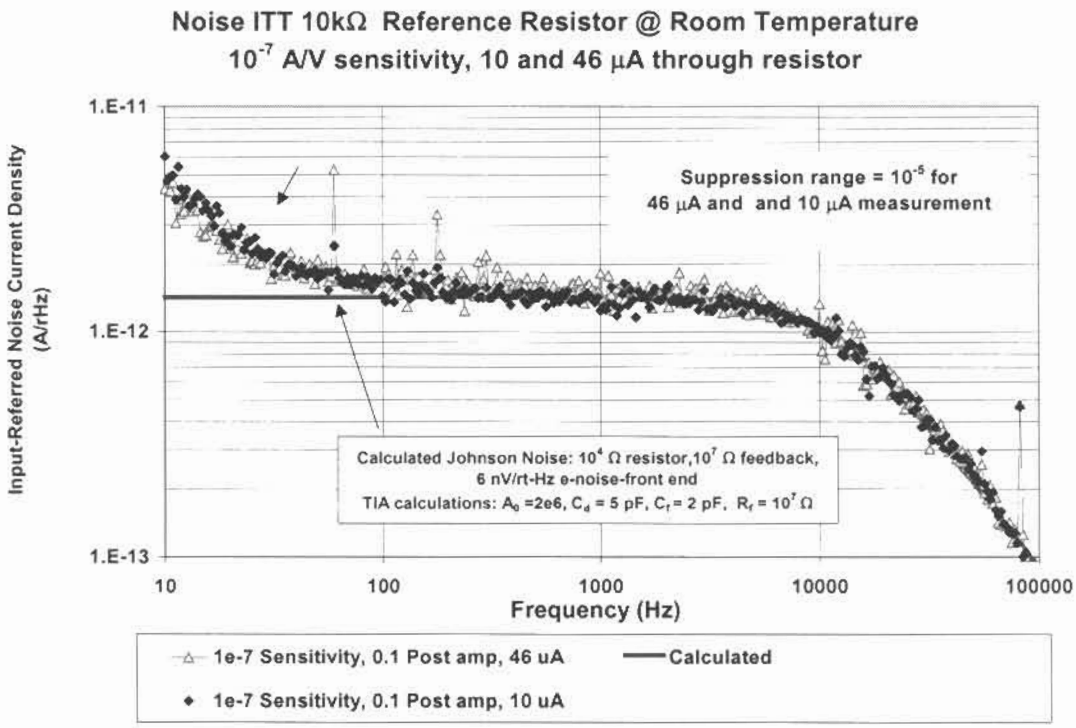


**Figure 3: Comparison of noise spectral density for two levels of current in the 10 kΩ test resistor. Since the two spectra are identical we assume that current in the suppression circuitry does not interfere with noise measurements of HgCdTe diodes with leakage currents in this range.**

Note that all of the diodes have significant *1/f* noise components with only the lowest-noise diodes exhibiting purely "*1/f*-like" spectral characteristics. Also note that the lowest-noise spectra flatten out slightly somewhat between 6 and 12 kHz. This indicates that the white noise components (Johnson and Shot noise) are comparable to the *1/f* noise at these frequencies. The CrIS instrument requires detector performance for which the white noise component dominates in this frequency region. These spectra were acquired under dark conditions (no flux on the detectors), so the above curves are not likely the same as would be acquired under illumination where shot noise increases the white component of the noise.

In Figure 5 we compare the NSD for 10_5 (the lowest noise device) to the resistor NSD. Here we see that the photodiode NSD is 3-10 times larger than the resistor NSD in the frequency range of 10-1000 Hz in the range of bias currents and DL1211suppression settings tested. Since random noise adds in quadrature, at worst the *1/f* spectra below 1000 Hz might require a 10% correction. The diode NSD spectra were acquired at a suppression setting of 1e-4. The resistor data are acquired for settings of 1e-3 and 1e-5 bracketing the 1e-4 setting so we have confidence that the resistor data for the large bias currents represents a worst case. This leads us to believe that the DL1211 is not a significant factor in the HgCdTe detector measurements.

We also decided to try to determine the stability of the NSD measurement process. Shown in Figure 6 are 11 NSD plots for diode D10_5. Nine spectra were acquired at a detector bias of −70 mV, and one each at −50 mV and −100 mV. These spectra were acquired over a period of approximately 2 hours with the diode operating near 77.7 K. (There was a <u>very</u> slow drift in the temperature of the device as discussed below.) These data show that the measurement process is very repeatable at a fixed bias. We also performed repeatability testing for 4 other diodes and found similar stability in the measurement process. Note that the −100 mV NSD plot in Figure 9 is slightly higher than the main group of −70 mV bunched around the same value, the −50 mV NSD is slightly lower. This behavior is unexplained, but may indicate that the *1/f* noise depends on more than just photodiode current. It could also be an artifact of the DL1211, but that is unknown.

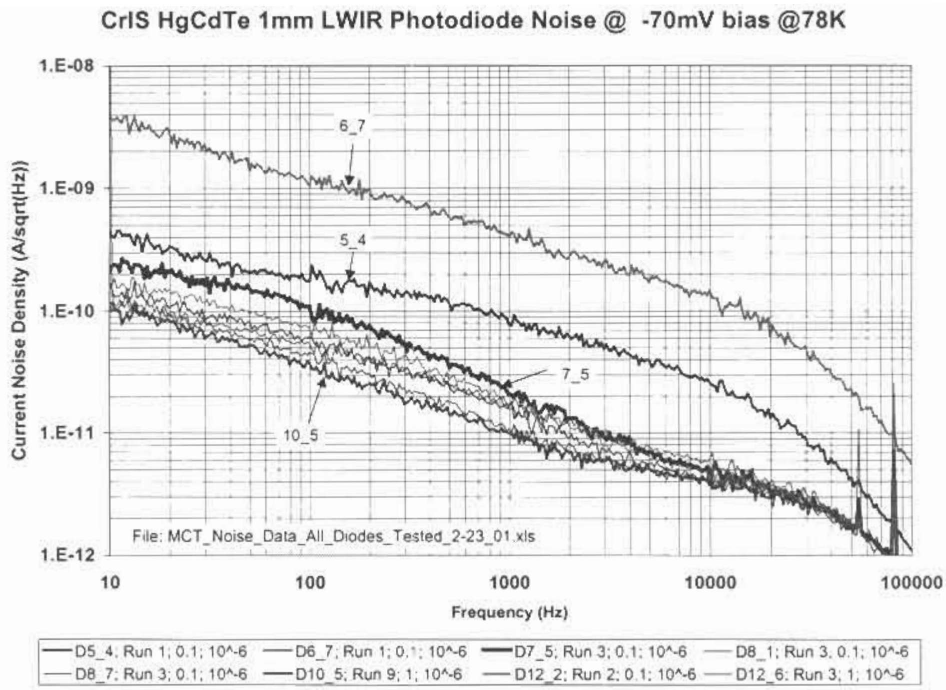


**Figure 4: Noise spectral density for 8 HgCdTe diodes studied. The lowest noise diode, denoted D10_5 shows the most *1/f*-like behavior along with D12_2.**

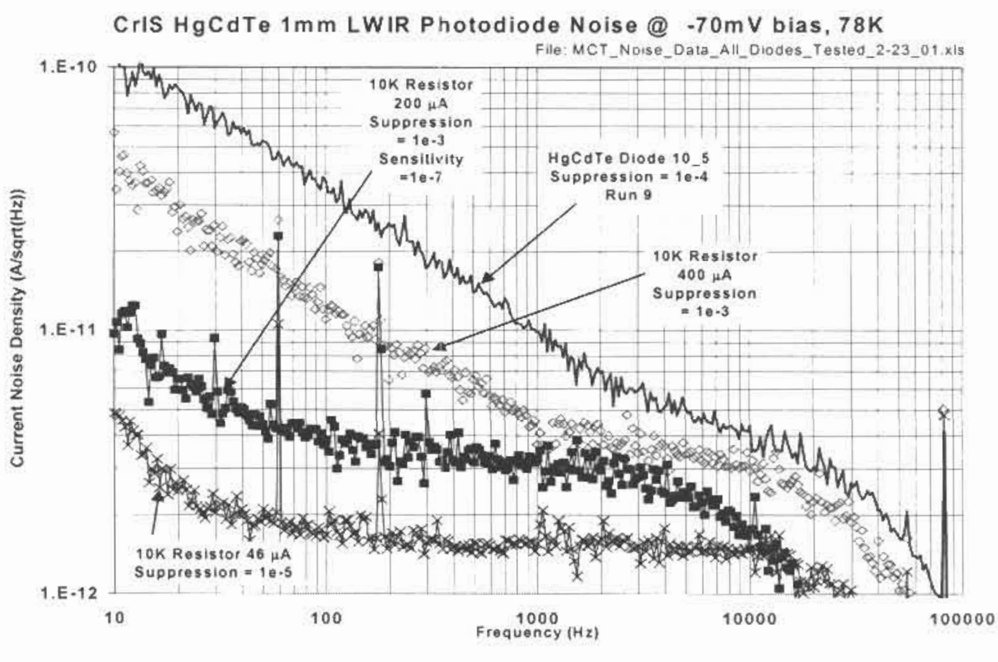


**Figure 5: Comparison of noise data for HdCdTe diode 10_5 (the lowest noise device tested in this group) to resistor data for various currents in the 10 kΩ resistor. Diode 10_5 suffered from about 50 μA of leakage current at –70 mV bias. Sensitivity setting is 1e-6 for all but the indicated 200 μA resistor measurement.**

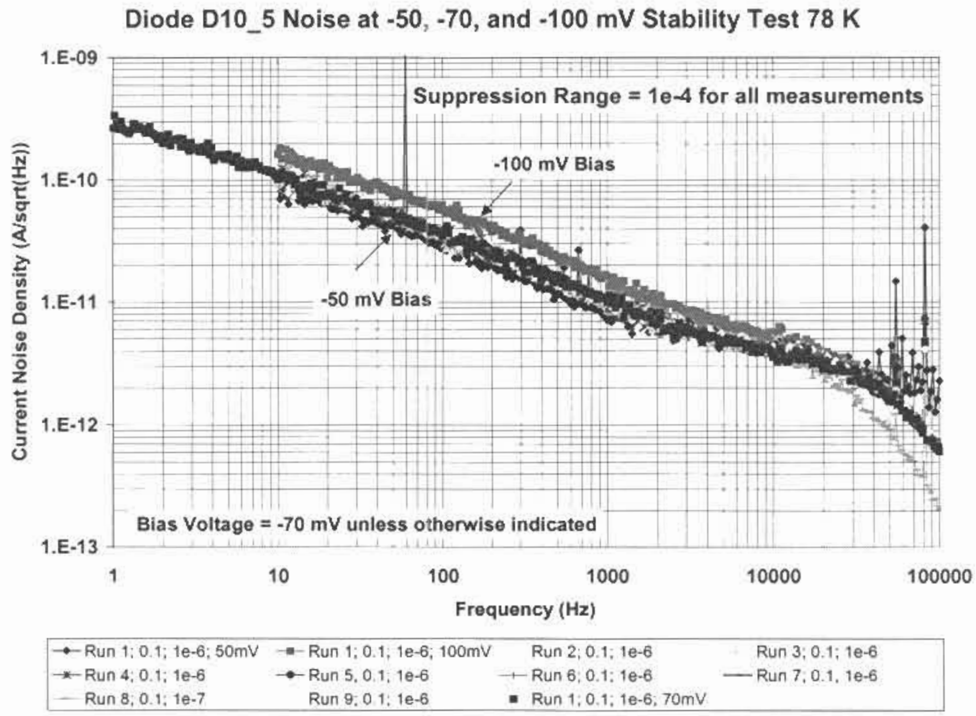


**Figure 6: NSD versus frequency for diode D10_5. The above NSD spectra were acquired over a period of >2 hours. Note that –70 mV NSD plots are tightly grouped near the same values. The –100 mV NSD is slightly higher and the –50 mV NSD slightly lower than the main group of –70 mV curves.**

As noted above the temperature of the diodes under test was generally changing very slowly during all noise spectra acquisitions described herein. Change in operating temperature of the devices during NSD data acquisition could induce a *1/f*-like behavior at the output of the DL1211 (d.c. drift) so we decided to carefully characterize NSD relative to temperature drift for one device. Figure 7 is a plot of the DL1211 d.c. output as a function of time with diode D12_2 under test. (Diode 12_2 was the second lowest noise device relative to 10_5 in this sample.) We acquired two noise spectra for this device under different temperature drift conditions. At time-0 on the chart in Figure 7 we adjusted the suppression circuitry of the DL1211 to produce a D.C. output near 0 V. We then allowed the D.C. output to drift monitoring it carefully for about 25 minutes. When it became apparent that the D.C. drift was stabilizing NSD data was taken. The first NSD measurement was made when the D.C. output had stabilized for several minutes near 3.3 V and the dewar/detector temperature sensor indicated that the temperature was stable. We continued to monitor the preamp D.C. output until it drifted near preamp saturation for the DL1211. At this point the temperature was changing rather rapidly at a rate near 10 mK/minute. We then readjusted the suppression to produce output near 0V and acquired the second NSD plot for D12_2 while the temperature was apparently changing rapidly.

In Figure 8 we see a comparison of the two NSD plots for D12_2. Since the two curves overlap each other almost perfectly it indicates that d.c. drift associated with diode temperature change at the rates observed here is probably not a major factor in the present measurements. However, one is cautioned to remember that this single point demonstration does not conclusively prove that d.c. drift is not a factor in this type of measurement. Adequate equilibrium conditions must be established for any measurement of *1/f* noise to ensure that the data acquired does not suffer from unknown or uncontrolled conditions. Note that just before and just after each NSD plot was acquired we recorded the dewar/detector temperature. The largest rate of change seen during the entire measurement sequence was 20 mK/minute (during testing of diode 5_4) with a typical rate in the 0-10 mK/minute range.

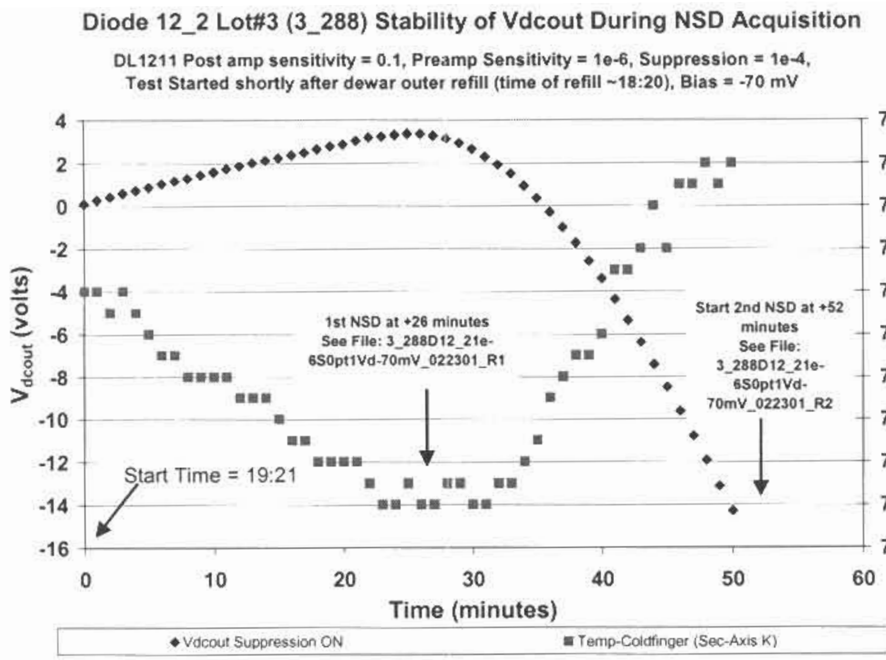


**Figure 7: D.C. drift of DL1211 preamp output (suppression ON @ 1e-4) as a function of time. Temperature drift rates typically ranged from 0 to ~10 mK/minute. LWIR detector leakage current strongly depends on temperature.**

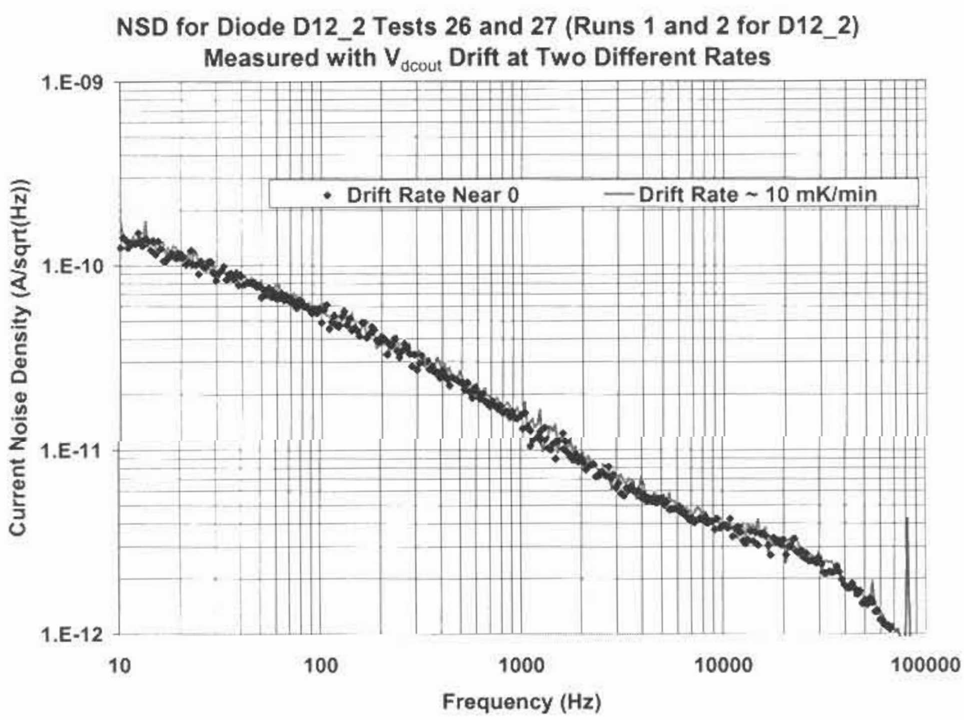


**Figure 8: NSD plots for D12_2 with different rates of temperature drift. Identical spectra indicate that some temperature drift rate (in this case ~ 10 mK/minute) probably does not invalidate *1/f* noise measurement.**

It is worthwhile to consider the rate of change of d.c. output of the test setup we would expect for HgCdTe diodes. Over a long period of time Rockwell Scientific/DRS-Anaheim and ITT have been collecting HgCdTe performance data as a function of operating temperature. It has been experimentally observed that for LWIR diodes with cutoffs near 16 microns the temperature dependence of the leakage current near 78 K varies with temperature according to the following:

$$I(T) \sim I(78K) * (T/78)^{10.2}$$ **Equation 4**

Using Equation 4 we can estimate the expected d.c. drift based on the measured temperature of diode D12_2. In Figure 9 we show the same data presented in Figure 7 except compared to calculated d.c. output (solid line in Figure 9) based on the above temperature dependence.

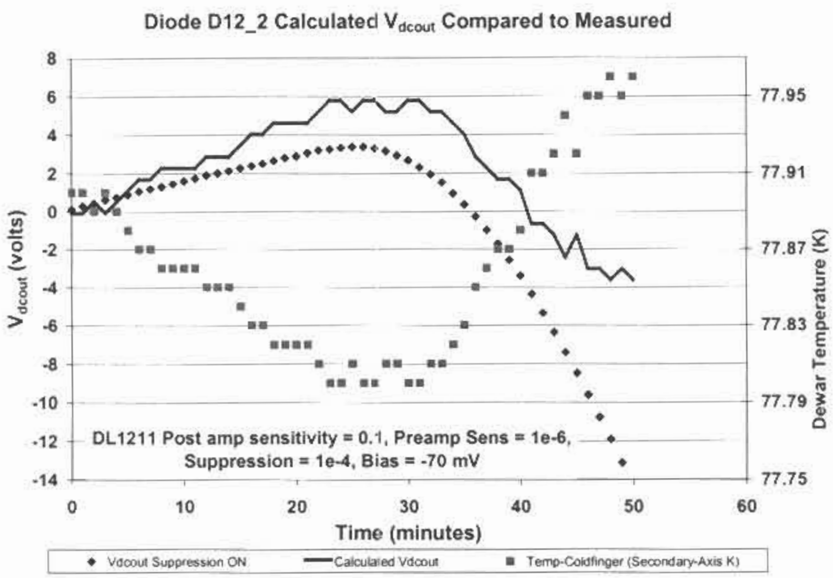


**Figure 9: $V_{dcout}$ should change rapidly with diode temperature. Solid line shows the amount of d.c. drift expected based on experimentally observed rates of change of HgCdTe diode leakage current with temperature.**

This data may indicate that there is a phase lag or difference between the dewar temperature sensor and the actual temperature of the detector. (The temperature sensor is close to the location of the diode under test, but is not directly in the diode package.) Nevertheless it is clear that the d.c. output of the DL1211 preamp and the temperature of the diode are correlated. It is also possible that the DL1211 suppression circuitry drifts and results in further complication of the process. From one set of data it is of course impossible to draw too many conclusions so this particular behavior requires more study to completely explain.

One final correlation that should be noted is between current-voltage characteristics and noise. Current versus voltage at 77 K for the devices tested in this effort are shown in Figure 10. The three noisiest diodes (See Figure 4) are diodes suffering from the largest leakage currents in reverse bias. One the other hand, one of the two lowest-noise diodes is 12_2 and it happens to be the lowest-leakage diode. Diode 10_5 is the lowest noise device, but it in the mid-range when it comes to I-V so the correlation is not exact. However, it is clear that these curves suggest that the better the I-V curve the lower the noise will be. Given that *1/f* noise is expected to be proportional current this makes sense. More data from a much larger sample of devices must be acquired before any useful conclusions can be drawn. If the correlation between I-V curve and noise performance turns out to be strong over a large enough sample we may be able to use the I-V curve alone as the first screening criterion for the CrIS 1mm diodes.

Current *versus* Voltage CrIS 1 mm Diodes at 77 K 3-288

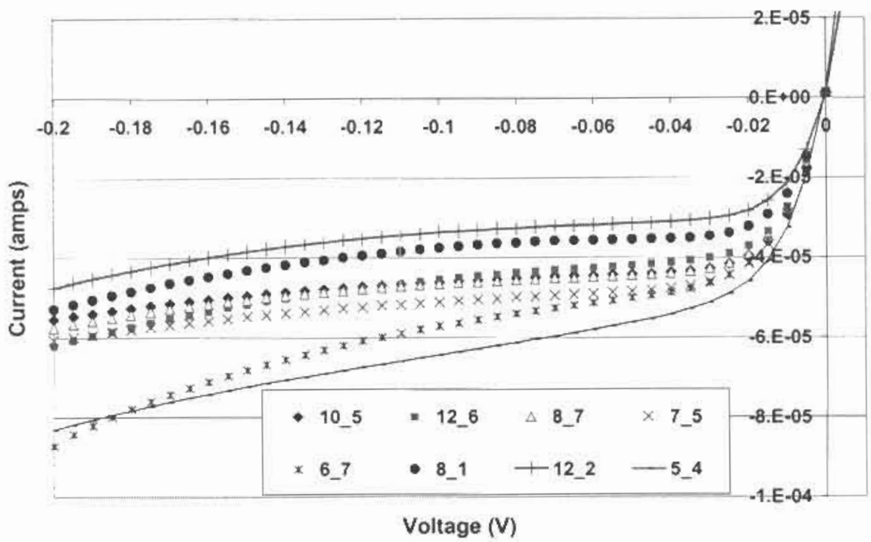


**Figure 10 I-V curves for the diodes tested in this effort correlate with noise behavior. Low-noise diodes (10_5 and 12_2) have relatively good I-V curves while the three diodes with highest leakage current (6_7, 5_4, and 7_5) are the three highest noise samples.**

## 4. Conclusions and Discussion

The quality of noise measurement for detectors is often determined by equipment used to test the devices instead of the devices themselves. In the measurements described herein we have seen that the DL1211 does not appear to limit the measurement of *1/f* noise in the devices we tested. The reader should be cautioned that this is not always the case, and should consider careful determination of test equipment and environmental limitations in any such measurement. During the tests described herein we acquired enough DL1211 data to indicate that the amplifier was not significantly limiting our ability to measure *1/f* noise for the HgCdTe devices we tested. However, much more data could have been taken to establish the limitations of the instrument's measurement capabilities under a wider range of measurement conditions. Manufacturers of such equipment cannot usually afford to provide test data for all possible conditions so it is incumbent on the user to establish this for each test.

*1/f* noise often imposes a severe limitation on the performance of space instruments. In the case of the CrIS instrument (interferometer-based) the frequency band of interest is the 6-12 kHz band. The devices tested in this effort show significant dark *1/f* noise in this range. However, the CrIS instrument design results in significant background flux on the detectors. This increases the shot noise contribution to total NSD and results in essentially a flat noise spectrum for the LWIR bands in this frequency range for detectors with 1/f noise spectra similar to D10_5 and D12_2 tested here.

## 5. ACKNOWLEDGEMENTS


Thanks to Dr. Fergus Moore of ITT A/CD (Fort Wayne) for providing the TIA frequency response expression (Equation 1) used to fit the resistor noise data .


## 6. REFERENCES


1. A.I. D'Souza et al, *Noise in Large Area CrIS $Hg_{1-x}Cd_xTe$ Photovoltaic Detectors*, SPIE Conference 4820 (Seattle) Proceedings, July 2002

2. Jan Archambault, DL Instruments, Private Communication

NPOESS IPO/ADA
Capt Christina Meuth



# Measurement of Noise in Large Area $Hg_{1-x}Cd_xTe$ Photovoltaic Detectors: Validation/Analysis of Results

D.S. Smith
ITT Industries, 1919 W. Cook Road, Ft. Wayne, IN 46814

A.I. D'Souza
DRS Sensors & Targeting Systems, 3400 Miraloma Avenue, Anaheim, CA 92806

## ABSTRACT

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Cross-track Infrared Sounder (CrIS) is a Fourier Transform interferometer-based sensor used to measure earth radiance at high spectral resolution and low spatial resolution. Measured radiance data are analyzed by end users to provide pressure, temperature and moisture profiles of the atmosphere. The CrIS instrument contains Mercury-Cadmium-Telluride (MCT) photovoltaic (PV) detectors with spectral response in the SWIR ($\lambda_c \sim 5$ μm at 98K), MWIR ($\lambda_c \sim 9$ μm at 98K) and LWIR ($\lambda_c \sim 15$ μm at 81K) ranges. The CrIS instrument requires large area detectors (1mm diameter) with state-of-the-art detector performance at temperatures attainable with passive cooling.

In the case of the LWIR bands noise associated with the detectors limit the instrument performance. In this paper we describe a study of the noise characteristics of a sample of CrIS MCT PV detectors, emphasizing acquisition and validation of *1/f* noise measurements for these devices. Interesting aspects of the *1/f* noise dependence on bias-voltage and bias-current are noted. The results are analyzed further in a companion paper[1] that emphasizes the relationship between leakage current mechanisms in the diodes and *1/f* noise observed.

**Keywords:** detectors, noise, noise measurement

## 1. INTRODUCTION

Accurate measurement of *1/f* noise (or noise in general for that matter) requires that we determine that the equipment used to measure the noise does not limit the measurement of the components under scrutiny. In all measurements described herein we used a commercially available TIA (TransImpedance Amplifier) from



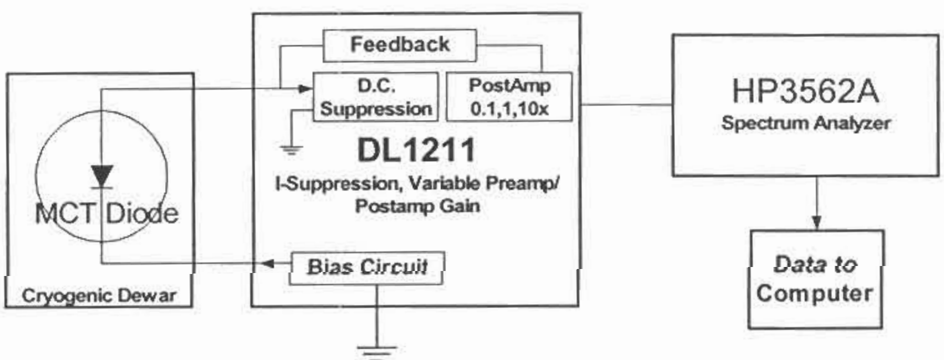


**Figure 1 HgCdTe longwave Diodes were tested under no background flux in a blinded dewar. The DL1211 is a current preamplifier capable of diverting d.c. current resulting from the bias on the detector from the feedback circuit reducing the d.c. offset at the output of the DL1211's preamp.**

DL Instruments (model DL1211) to transform noise current density of the detectors under test to a noise voltage density measurable by a HP3562 spectrum analyzer, as shown in figure 1.

The DL1211 (connected to the detector through a dewar bulkhead) is an instrument used in many laboratories to perform detector signal and noise measurements. According to the manufacturer of the DL1211 its feedback resistors, which range from 1 kΩ up to $1\times10^{11}$ Ω, suffer from low *1/f* noise. The level of the *1/f* noise associated with the DL1211 is indicated by the measurement results offered herein.

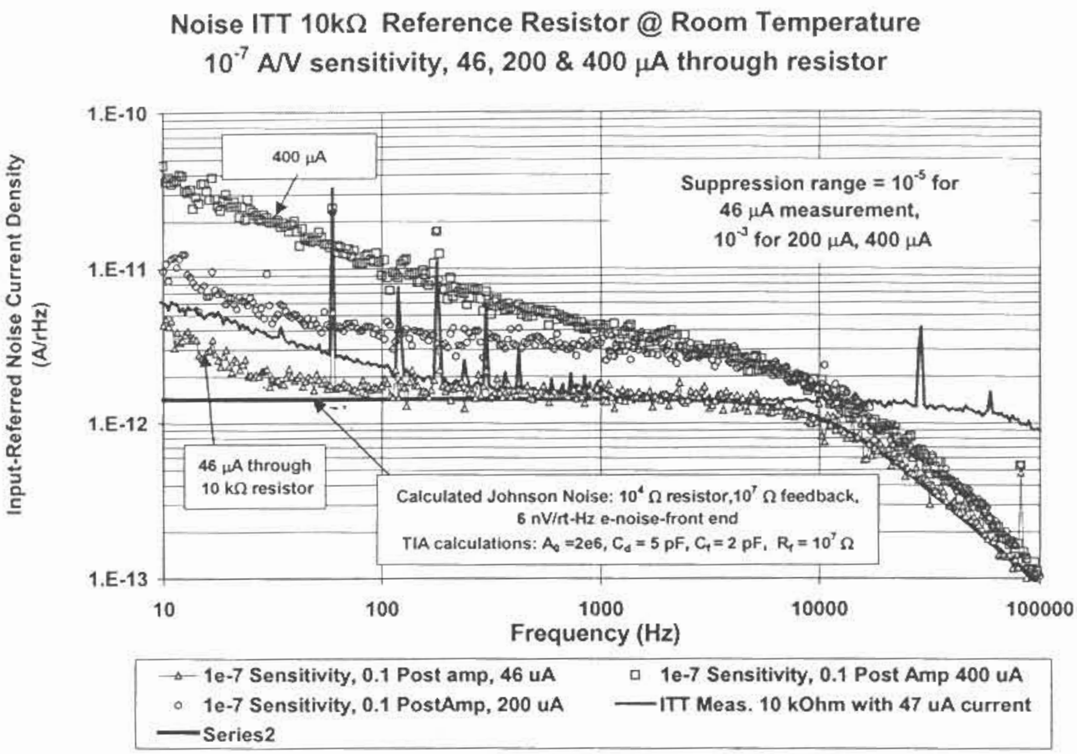


**Figure 2 Noise-current spectral density for a 10 kΩ resistor for several currents in the resistor. The suppression range affects the white noise of the measurement as well as the 1/f components.**

## 2. Resistor Measurements

To simulate the conditions for operation of the DL1211 during HgCdTe diode testing we decided to study a "known" component with bias currents similar to the HgCdTe leakage currents. We measured spectral noise voltage density produced by a 10 kΩ resistor with various bias currents passing through the resistor. We chose this value because the photodiodes under test exhibit dynamic impedances on the order of 10 kΩ. Shown in figure 2 are noise current spectral density (NSD) plots of the 10 kΩ resistor referred to the input by scaling the voltage noise spectral density using the DL1211 preamp transimpedance and post-amp gain. (The noise voltage spectral density is divided by the feedback resistor value and the DL1211 post-amp gain.) The lowest noise curve shown (indicated with triangles) was acquired with 46 µA bias current in the resistor. We also show a plot of calculated NSD (solid curve constant in value between 10 and 100 Hz) for 10 kΩ and a 6 nV/rHz voltage noise at the front end of the DL1211. Further, the resistor NSD was measured at ITT using a custom-built preamp used for detector testing. The data for the ITT characterization are shown in the solid noise curve and compare well with the DL1211 results. Since the DL1211 results were actually slightly better than the results for the ITT custom preamp it was concluded that no further comparison of the performance of the DL1211 relative to the ITT custom preamp was needed. Data reported herein (except for the ITT-measured NSD in Figure 2) were acquired with the DL1211.

Expected noise, $I_n$, in figure 2 is calculated using the following equations:

$$g(\omega)=\left\{\frac{1}{A_0}\left(1+\frac{i\omega}{\omega_t}\right)\left(1+\frac{R_f}{R_d}+i\omega R_f(C_f+C_d)\right)+\left(1+i\omega R_f C_f\right)\right\}^{-1} \quad \textbf{Equation 1}$$

$$i_n^2 = 4k_b\left(\frac{T_f}{R_f}+\frac{T_d}{R_d}\right)+\omega^2 e_n^2 C_d + e_n^2\left(\frac{1}{R_f}+\frac{1}{R_d}\right)^2 \qquad \textbf{Equation 2}$$

$$I_n(\omega) = i_n(\omega)g(\omega) \qquad \textbf{Equation 3}$$

where $R_f$ and $R_d$ represent resistance values of the feedback and the resistor/detector respectively. $C_f$ and $C_d$ are capacitance values associated with the feedback and input node of the DL1211. $e_n$ is front-end voltage noise of the amplifier, $k_b$ is Boltzman's constant, $T_d$ is the operating temperature of the device, and $T_f$ is the operating temperature of the DL1211 amplifier. ω is the frequency in radians/sec ( = $2\pi f$, $f$ in Hz). Note: in many of the charts we refer to a sensitivity setting of the DL1211. The feedback resistor referred to in equations 1 and 2 is given by 1/(Sensitivity setting in $\Omega^{-1}$), i.e. DL1211 Sensitivity Setting = 1/ $R_f$.

The plot as presented in figure 2 shows noise current density with an apparent roll-off near 10 kHz. The roll-off is a result of frequency response of the DL1211 for the feedback (see equation 1) and post-amp settings used for the test, and is not a characteristic of the input noise itself (See equation 2.). Also note that shot noise is not shown because resistors do not suffer from this form of noise.

The data and calculation in Figure 2 show that with reasonable assumptions for the DL1211 preamplifier we can account for the impact of noise in the measurement circuit. This is important in establishing limits on how well we can measure *1/f* noise of the MCT diodes with the DL1211. Also note two other measured noise curves in Figure 2. In squares and circles (the two highest-level noise curves at 10 Hz) we show the noise curves of the 10 kΩ resistor measured at 200 μA and 400 μA bias currents. We acquired this data with a less sensitive bias current suppression range than used for the 46 μA measurement. Even though the *1/f* noise component increases the shapes and slopes are similar, with the *1/f* noise contribution increasing with the current. However, the unexplained behavior is the rapid increase of the *1/f* noise component with current. It appears that the *1/f* noise voltage density increased by a factor of 4 with only an increase of a factor of 2 in current flowing through the resistor. As explained in reference 1, *1/f* noise voltage spectral density in a photodiode typically scales with the current. The behavior seen in Figure 2 for the resistor suggests that there is a far more rapid increase with current for some components of *1/f* noise, or possibly that there are more sources of *1/f* noise than accounted for in our measurement. Either way we did not acquire enough data for this experiment to answer this particular question.

The white noise (flat) regions of the 200 and 400 μA spectra show a noise increase relative to the 46 μA white noise probably best associated the suppression circuitry. Since the white noise component increases far less rapidly than the *1/f* noise, one could speculate that the suppression circuit's noise is from a source (Johnson or Shot) in the suppression circuitry itself.

Further consideration of the variation of the resistor *1/f* noise with current is warranted since that is what we are attempting to measure in the MCT diodes. In figure 3 we see a comparison of the noise measured for the 10 kΩ resistor with 10 μA and 46 μA flowing through the resistor. The DL1211 settings are the same for both measurements as noted on the figure. Since both curves overlap within the apparent noise of the measurement it appears that small currents through the resistor are a weak factor for determining resistor *1/f* for this range of currents. This suggests that the DL1211 may be the source of the *1/f* noise instead of the resistor. The DL1211 is also possibly the source of the excess *1/f* noise seen in Figure 2 for the 200 μA to 400 μA cases where the noise increase depends strongly on the current.

## 3. HgCdTe Photodiode Measurements

The objective of these measurements is to determine the *1/f* noise characteristics of HgCdTe diodes for the CrIS program. We must then establish the NSD levels of the HgCdTe diodes relative to the DL1211 circuit used to characterize them to establish confidence in the measurements. In figure 4 we show a noise curves for all the HgCdTe diodes characterized in this experiment.

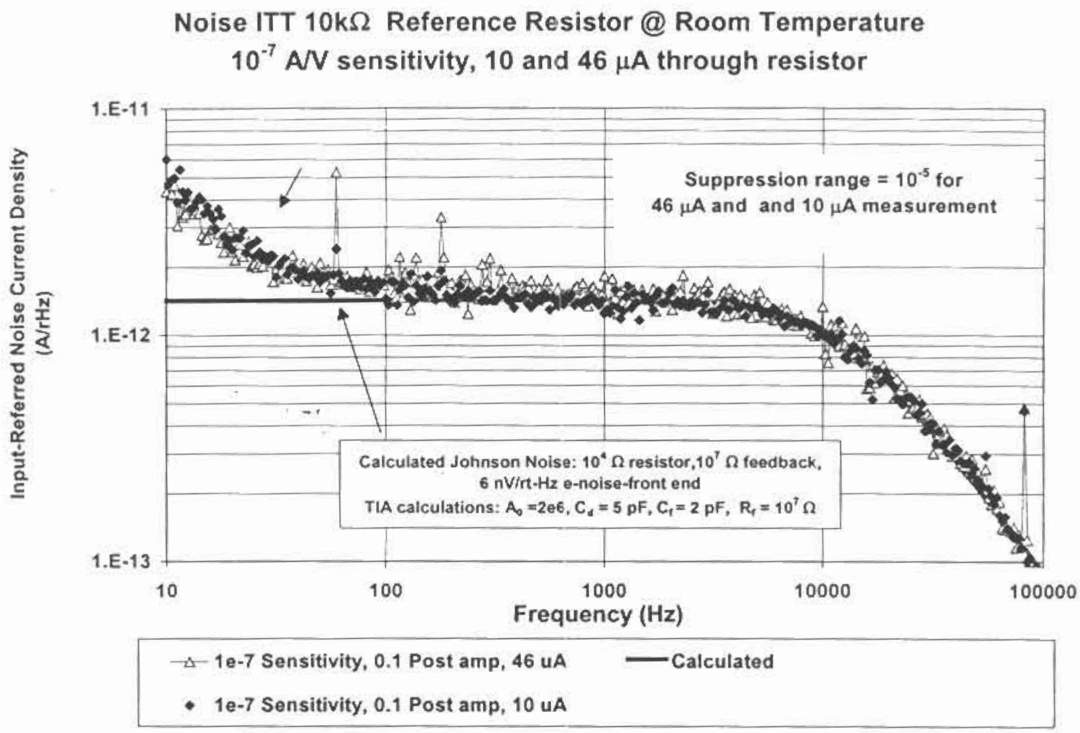


**Figure 3: Comparison of noise spectral density for two levels of current in the 10 kΩ test resistor. Since the two spectra are identical we assume that current in the suppression circuitry does not interfere with noise measurements of HgCdTe diodes with leakage currents in this range.**

Note that all of the diodes have significant *1/f* noise components with only the lowest-noise diodes exhibiting purely "*1/f*-like" spectral characteristics. Also note that the lowest-noise spectra flatten out slightly somewhat between 6 and 12 kHz. This indicates that the white noise components (Johnson and Shot noise) are comparable to the *1/f* noise at these frequencies. The CrIS instrument requires detector performance for which the white noise component dominates in this frequency region. These spectra were acquired under dark conditions (no flux on the detectors), so the above curves are not likely the same as would be acquired under illumination where shot noise increases the white component of the noise.

In Figure 5 we compare the NSD for 10_5 (the lowest noise device) to the resistor NSD. Here we see that the photodiode NSD is 3-10 times larger than the resistor NSD in the frequency range of 10-1000 Hz in the range of bias currents and DL1211suppression settings tested. Since random noise adds in quadrature, at worst the *1/f* spectra below 1000 Hz might require a 10% correction. The diode NSD spectra were acquired at a suppression setting of 1e-4. The resistor data are acquired for settings of 1e-3 and 1e-5 bracketing the 1e-4 setting so we have confidence that the resistor data for the large bias currents represents a worst case. This leads us to believe that the DL1211 is not a significant factor in the HgCdTe detector measurements.

We also decided to try to determine the stability of the NSD measurement process. Shown in Figure 6 are 11 NSD plots for diode D10_5. Nine spectra were acquired at a detector bias of –70 mV, and one each at –50 mV and –100 mV. These spectra were acquired over a period of approximately 2 hours with the diode operating near 77.7 K. (There was a <u>very</u> slow drift in the temperature of the device as discussed below.) These data show that the measurement process is very repeatable at a fixed bias. We also performed repeatability testing for 4 other diodes and found similar stability in the measurement process. Note that the –100 mV NSD plot in Figure 9 is slightly higher than the main group of –70 mV bunched around the same value, the –50 mV NSD is slightly lower. This behavior is unexplained, but may indicate that the *1/f* noise depends on more than just photodiode current. It could also be an artifact of the DL1211, but that is unknown.

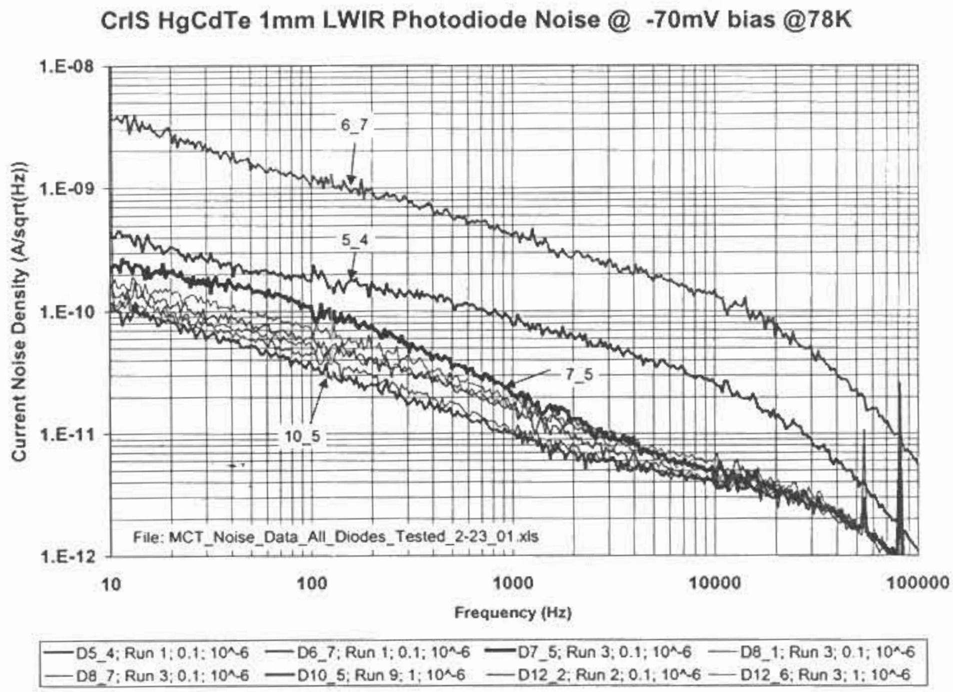


**Figure 4: Noise spectral density for 8 HgCdTe diodes studied. The lowest noise diode, denoted D10_5 shows the most *1/f*-like behavior along with D12_2.**

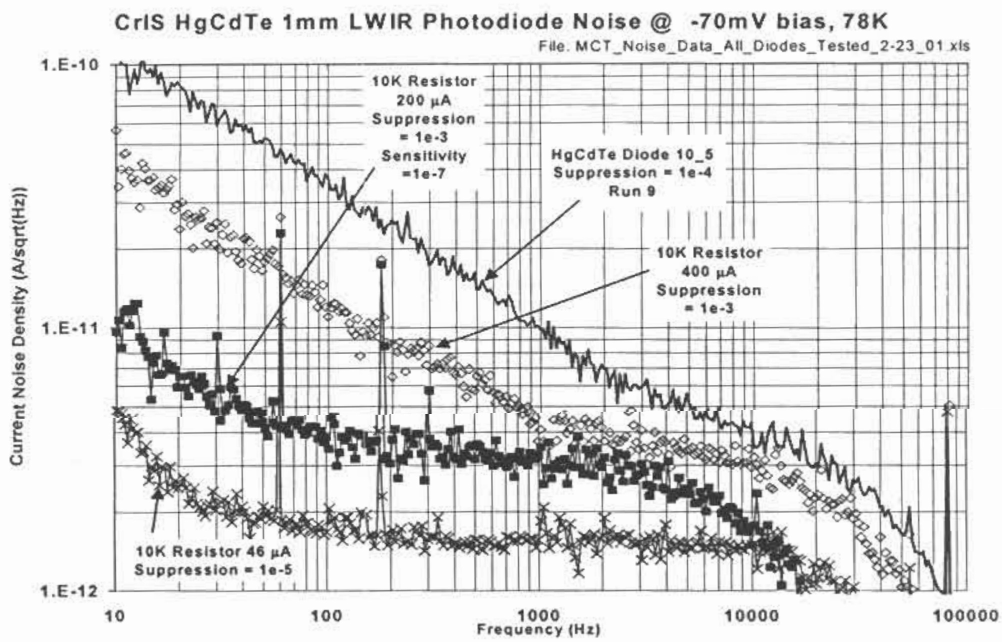


**Figure 5: Comparison of noise data for HdCdTe diode 10_5 (the lowest noise device tested in this group) to resistor data for various currents in the 10 kΩ resistor. Diode 10_5 suffered from about 50 µA of leakage current at –70 mV bias. Sensitivity setting is 1e-6 for all but the indicated 200 µA resistor measurement.**

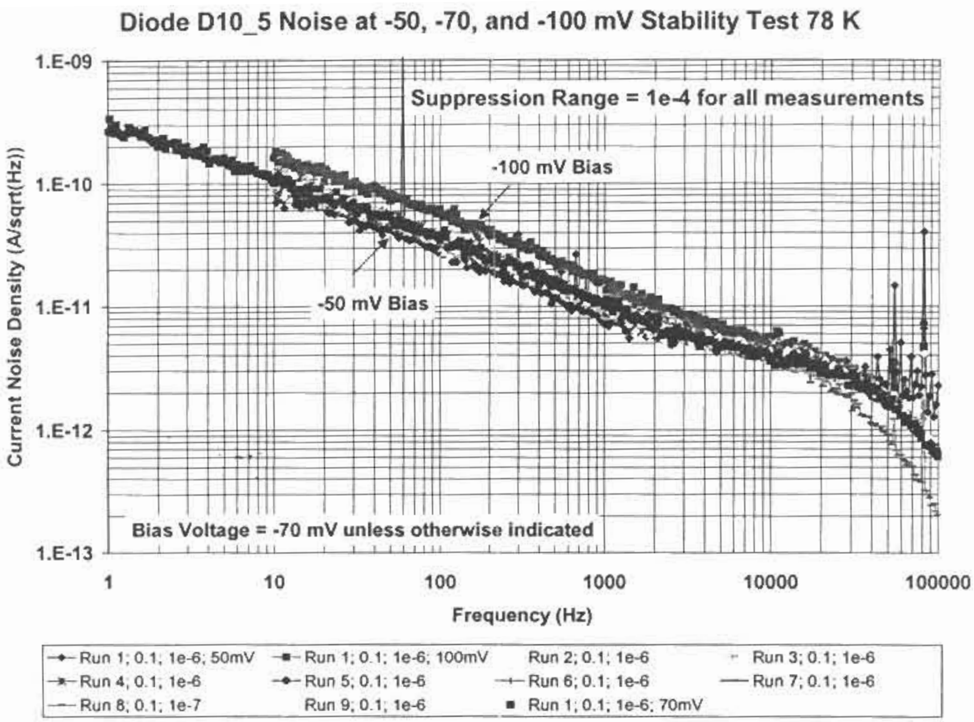


**Figure 6: NSD versus frequency for diode D10_5. The above NSD spectra were acquired over a period of >2 hours. Note that –70 mV NSD plots are tightly grouped near the same values. The –100 mV NSD is slightly higher and the –50 mV NSD slightly lower than the main group of –70 mV curves.**

As noted above the temperature of the diodes under test was generally changing very slowly during all noise spectra acquisitions described herein. Change in operating temperature of the devices during NSD data acquisition could induce a *1/f*-like behavior at the output of the DL1211 (d.c. drift) so we decided to carefully characterize NSD relative to temperature drift for one device. Figure 7 is a plot of the DL1211 d.c. output as a function of time with diode D12_2 under test. (Diode 12_2 was the second lowest noise device relative to 10_5 in this sample.) We acquired two noise spectra for this device under different temperature drift conditions. At time-0 on the chart in Figure 7 we adjusted the suppression circuitry of the DL1211 to produce a D.C. output near 0 V. We then allowed the D.C. output to drift monitoring it carefully for about 25 minutes. When it became apparent that the D.C. drift was stabilizing NSD data was taken. The first NSD measurement was made when the D.C. output had stabilized for several minutes near 3.3 V and the dewar/detector temperature sensor indicated that the temperature was stable. We continued to monitor the preamp D.C. output until it drifted near preamp saturation for the DL1211. At this point the temperature was changing rather rapidly at a rate near 10 mK/minute. We then readjusted the suppression to produce output near 0V and acquired the second NSD plot for D12_2 while the temperature was apparently changing rapidly.

In Figure 8 we see a comparison of the two NSD plots for D12_2. Since the two curves overlap each other almost perfectly it indicates that d.c. drift associated with diode temperature change at the rates observed here is probably not a major factor in the present measurements. However, one is cautioned to remember that this single point demonstration does not conclusively <u>prove</u> that d.c. drift is not a factor in this type of measurement. Adequate equilibrium conditions must be established for any measurement of *1/f* noise to ensure that the data acquired does not suffer from unknown or uncontrolled conditions. Note that just before and just after each NSD plot was acquired we recorded the dewar/detector temperature. The largest rate of change seen during the entire measurement sequence was 20 mK/minute (during testing of diode 5_4) with a typical rate in the 0-10 mK/minute range.

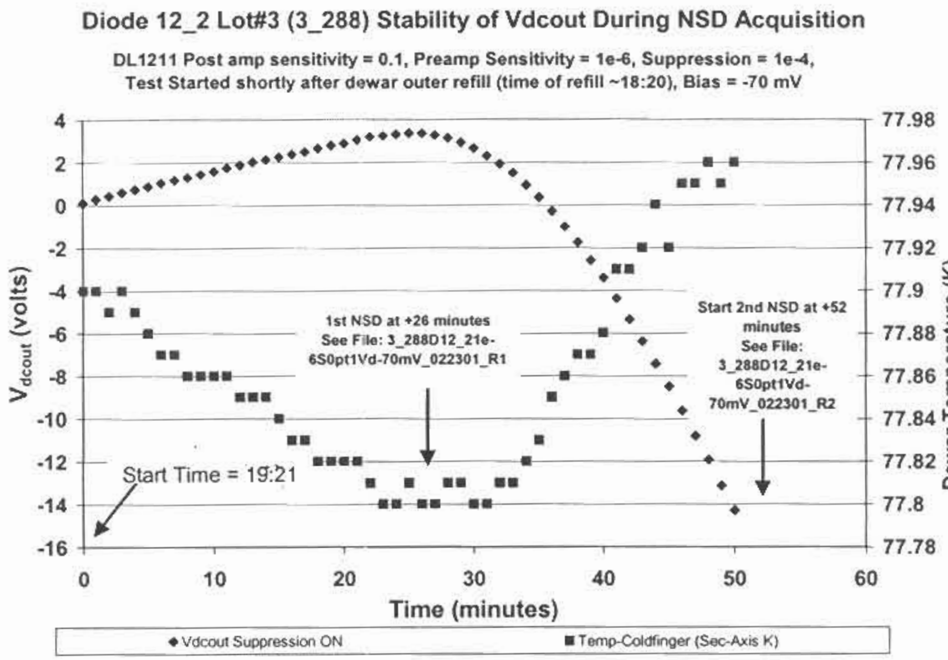


**Figure 7: D.C. drift of DL1211 preamp output (suppression ON @ 1e-4) as a function of time. Temperature drift rates typically ranged from 0 to ~10 mK/minute. LWIR detector leakage current strongly depends on temperature.**

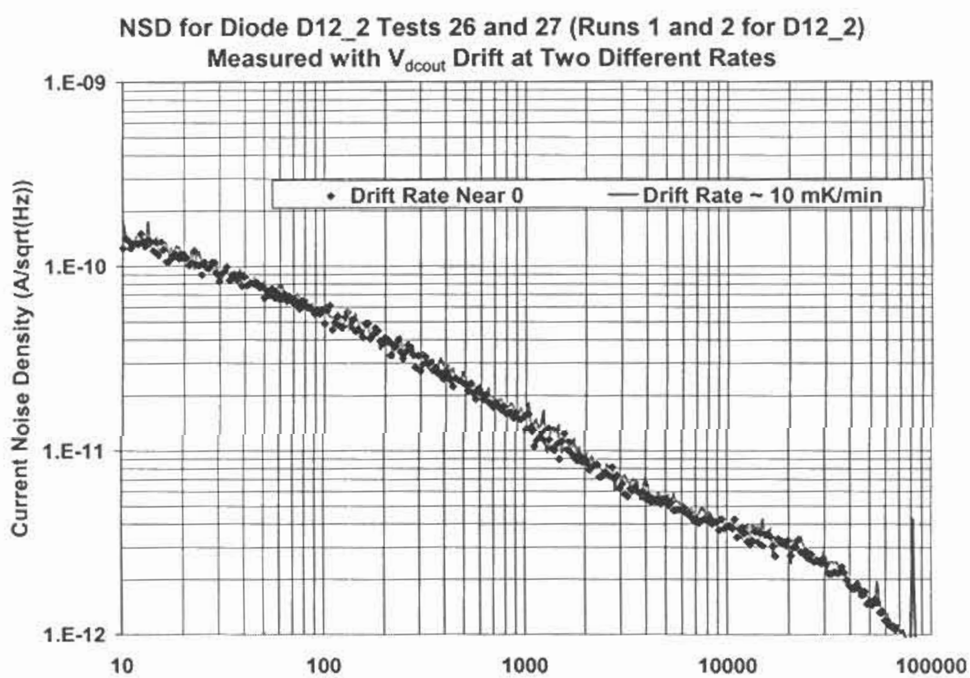


**Figure 8: NSD plots for D12_2 with different rates of temperature drift. Identical spectra indicate that some temperature drift rate (in this case ~ 10 mK/minute) probably does not invalidate *1/f* noise measurement.**

It is worthwhile to consider the rate of change of d.c. output of the test setup we would expect for HgCdTe diodes. Over a long period of time Rockwell Scientific/DRS-Anaheim and ITT have been collecting HgCdTe performance data as a function of operating temperature. It has been experimentally observed that for LWIR diodes with cutoffs near 16 microns the temperature dependence of the leakage current near 78 K varies with temperature according to the following:

$$I(T) \sim I(78K) * (T/78)^{10.2} \qquad \textbf{Equation 4}$$

Using Equation 4 we can estimate the expected d.c. drift based on the measured temperature of diode D12_2. In Figure 9 we show the same data presented in Figure 7 except compared to calculated d.c. output (solid line in Figure 9) based on the above temperature dependence.

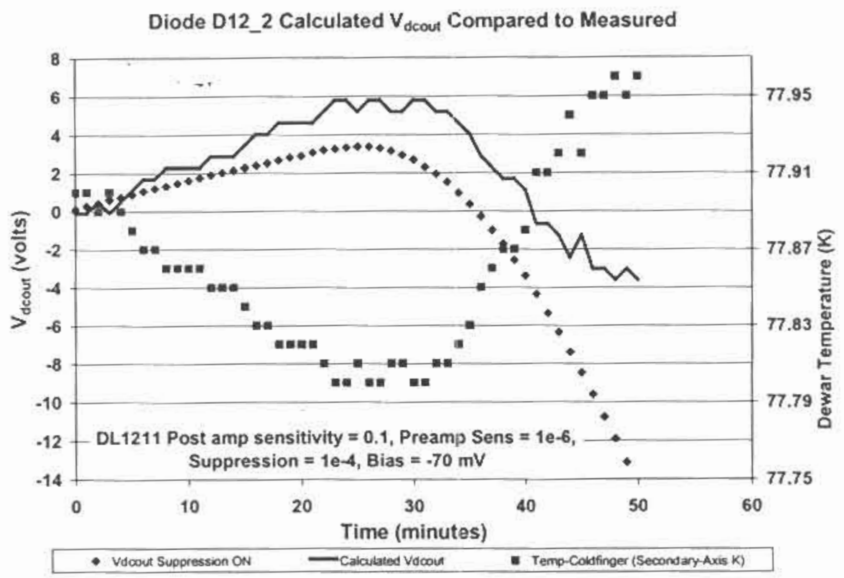


**Figure 9: $V_{dcout}$ should change rapidly with diode temperature. Solid line shows the amount of d.c. drift expected based on experimentally observed rates of change of HgCdTe diode leakage current with temperature.**

This data may indicate that there is a phase lag or difference between the dewar temperature sensor and the actual temperature of the detector. (The temperature sensor is close to the location of the diode under test, but is not directly in the diode package.) Nevertheless it is clear that the d.c. output of the DL1211 preamp and the temperature of the diode are correlated. It is also possible that the DL1211 suppression circuitry drifts and results in further complication of the process. From one set of data it is of course impossible to draw too many conclusions so this particular behavior requires more study to completely explain.

One final correlation that should be noted is between current-voltage characteristics and noise. Current versus voltage at 77 K for the devices tested in this effort are shown in Figure 10. The three noisiest diodes (See Figure 4) are diodes suffering from the largest leakage currents in reverse bias. One the other hand, one of the two lowest-noise diodes is 12_2 and it happens to be the lowest-leakage diode. Diode 10_5 is the lowest noise device, but it in the mid-range when it comes to I-V so the correlation is not exact. However, it is clear that these curves suggest that the better the I-V curve the lower the noise will be. Given that *1/f* noise is expected to be proportional current this makes sense. More data from a much larger sample of devices must be acquired before any useful conclusions can be drawn. If the correlation between I-V curve and noise performance turns out to be strong over a large enough sample we may be able to use the I-V curve alone as the first screening criterion for the CrIS 1mm diodes.

Current *versus* Voltage CrIS 1 mm Diodes at 77 K 3-288

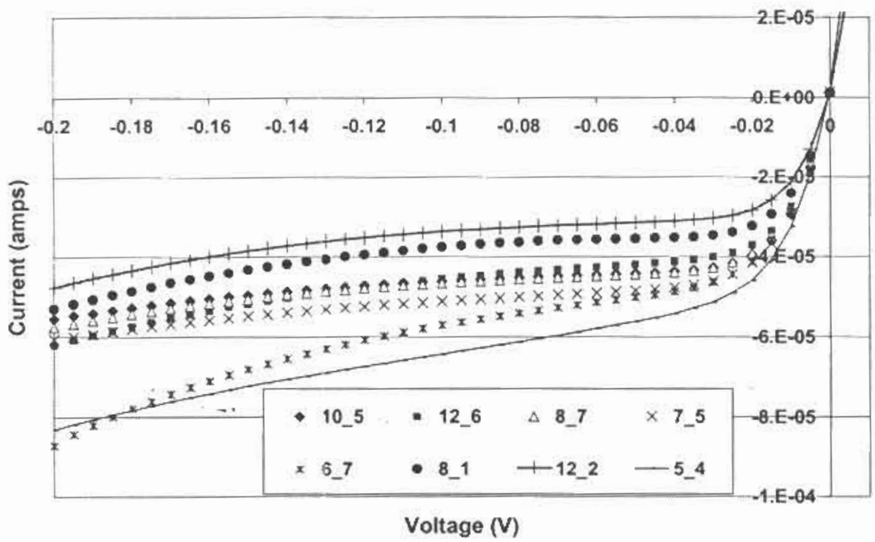


**Figure 10 I-V curves for the diodes tested in this effort correlate with noise behavior. Low-noise diodes (10_5 and 12_2) have relatively good I-V curves while the three diodes with highest leakage current (6_7, 5_4, and 7_5) are the three highest noise samples.**

## 4. Conclusions and Discussion

The quality of noise measurement for detectors is often determined by equipment used to test the devices instead of the devices themselves. In the measurements described herein we have seen that the DL1211 does not appear to limit the measurement of *1/f* noise in the devices we tested. The reader should be cautioned that this is not always the case, and should consider careful determination of test equipment and environmental limitations in any such measurement. During the tests described herein we acquired enough DL1211 data to indicate that the amplifier was not significantly limiting our ability to measure *1/f* noise for the HgCdTe devices we tested. However, much more data could have been taken to establish the limitations of the instrument's measurement capabilities under a wider range of measurement conditions. Manufacturers of such equipment cannot usually afford to provide test data for all possible conditions so it is incumbent on the user to establish this for each test.

*1/f* noise often imposes a severe limitation on the performance of space instruments. In the case of the CrIS instrument (interferometer-based) the frequency band of interest is the 6-12 kHz band. The devices tested in this effort show significant dark *1/f* noise in this range. However, the CrIS instrument design results in significant background flux on the detectors. This increases the shot noise contribution to total NSD and results in essentially a flat noise spectrum for the LWIR bands in this frequency range for detectors with 1/f noise spectra similar to D10_5 and D12_2 tested here.

## 5. ACKNOWLEDGEMENTS

Thanks to Dr. Fergus Moore of ITT A/CD (Fort Wayne) for providing the TIA frequency response expression (Equation 1) used to fit the resistor noise data .

## 6. REFERENCES

1. A.I. D'Souza et al, *Noise in Large Area CrIS $Hg_{1-x}Cd_xTe$ Photovoltaic Detectors*, SPIE Conference 4820 (Seattle) Proceedings, July 2002
2. Jan Archambault, DL Instruments, Private Communication